Determining productivity gains from herbaceous vegetation management with 'age-shift' calculations

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Summary

Gains in stand volume that result from competition control and fertilization are sometimes reported as 'percentage gains'. Because percentage gains arithmetically decline over time as stand volume increases, plantation managers have difficulty in using percentage gains to project growth and revenues. The 'age-shift' method quantifies the year advancements in stand growth due to silvicultural treatments and, for herbaceous vegetation management, it has been proposed that this metric is less likely to change after the juvenile growth phase. To test the sensitivity of the 'age-shift' method to time and hardwood competition, we used 20-year volume data from 11 loblolly pine (*Pinus taeda* L.) studies that had early complete herbaceous and woody competition control. Volume growth gains were expressed in terms of percentages and 'age-shifts'. On all sites with no woody competition, percentage gains declined from age 8 years to age 20 years. In contrast, age-shift estimates on these plots either remained constant or increased over time. However, in four cases where woody basal areas were greater than 4 m^2 ha^{-1} at age 15 years, age-shift gains due to herbaceous control decreased and eventually resulted in volume losses. When evaluating the response to early herbaceous competition control, age-shift calculations have promise as a useful predictive tool on sites with low levels of hardwood competition. Five methods for calculating age-shift are presented.

Introduction

Tree response to suppression of competing vegetation is often presented in absolute terms (e.g. individual tree measurements or stand volume) but early differences in growth between treated and untreated plots are sometimes presented as percentage gains (South and Barnett, 1986; Miller *et al.*, 1991; Harrison *et al.*, 2002; Stanturf *et al.,* 2003; Mead, 2005; Wagner *et al.*, 2006).

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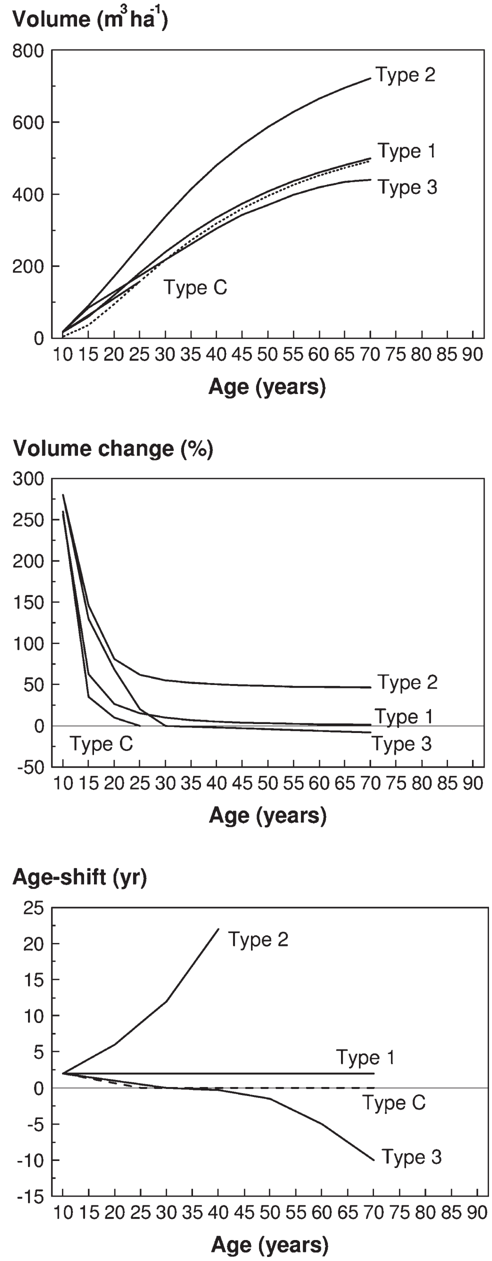
However, with acquisition of longer-term response data, it is apparent that percentage gains in stand volume are a function of stand age or size (Knowe and Foster, 1989; South, 1991, 1993; Kirongo and Mason, 2003). Perhaps for all tree species, unrealistic projections will occur if percentage gains at age 7 years are used to estimate volume gains at age 40 years. The age-shift method (i.e. quantifying year advancements in growth due to silvicultural applications) might be a more useful measure of projecting tree response for both economists and silviculturists. The method involves plotting stand volume over time for both treated and non-treated stands and then calculating the difference in *x*-coordinates at a selected age of the treated stand.

For hardwoods, the age-shift method has been used to determine the economics of a 20-year age-shift (Siry *et al*., 2004). For loblolly pine (*Pinus taeda* L.), this method has been used to project measurements at ages 9–11 years to the end of the rotation (Huang and Teeter, 1990; Lauer *et al*., 1993; Miller *et al*., 1995a). However, researchers have not determined if an age-shift estimate made at an early age will remain constant over time. If the initial age-shift estimate is greater than that determined a decade or two later, then this method of projecting volume production might also overestimate realized volume gains at harvest. Therefore, the main objective of this paper was to determine if age-shift estimates are stable over time (with respect to early herbaceous control treatments in *Pinus taeda* L. plantations). Hypotheses tested were: (1) in the absence of hardwood competition, the age-shift gain resulting from control of herbaceous plants does not decrease after age 8 years; (2) in the presence of hardwood competition, the age-shift gain due to controlling herbaceous plants does not decrease after stand age 8 years; (3) the age-shift gain resulting from control of both herbaceous and woody plants does not decrease over time; (4) the percentage gain resulting from control of herbaceous plants does not decrease from age 8 to age 20 years; and (5) the age-shift method based on height gains at age 9 years are equivalent to estimates based on volume gains at stand age 8 years.

A secondary objective was to illustrate how the age-shift method can be used to classify silvicultural treatments. When developing growth and yield models, biometricians sometimes group silvicultural treatments into one of several response types (Mason and Milne, 1999; Nilsson and Allen, 2003; VanderSchaaf and South, 2004). Plotting age-shift values over time can help researchers identify the type of response expected from the silvicultural treatment (Figure 1).



Materials and methods

Long-term data needed for testing came from the region-wide network of the Competition Omission Monitoring Project (COMProject) (Miller *et al.*, 2003a, b) with the most recent, unpublished age-20-years data added. A factorial experimental design was utilized at 13 sites in seven southern US states and across four physiographic provinces ranging from latitudes 30° to 37° N. The studies were established on medium to high productivity sites that ranged in site index (base age 25 years) from 17 m (Appomattox, VA) to 25 m (Bainbridge, GA). Soil and site location details have been reported previously (Miller *et al.*, 1995b, 2003a).

Each study involved four treatments that were replicated at least four times. Treatment plots were generally 0.1 ha, and interior measurement plots were 0.036 ha. Planting spots were on a 2.74 × 2.74 m grid (1329 ha^{-1}) except at Pembroke, GA (1396 ha^{-1}) and Arcadia, LA (1537 ha^{-1}) where seedlings were operationally planted. Genetically improved seedlings were used. Each measurement plot consisted of 49 permanently tagged pines and was surrounded by two border rows. The four treatments were as follows.

W+H: a mixture of woody and herbaceous competition. After initial site preparation to reduce all woody vegetation to ground level, no further weed control treatments were applied.

H: herbaceous competition. Foliar and basal sprays as well as basal wipes were applied to hardwoods and woody shrubs in a manner to minimize injury to pines and herbaceous plants. One or two herbicide applications were made before planting pines and multiple post-emergence herbicide applications were made during the first 3–5 years after planting. Herbicide treatments usually included directed sprays (glyphosate, triclopyr and picloram) and later basal wipes with triclopyr plus a penetrant and diesel fuel to minimize any potential damage to pines and herbaceous plants.

W: woody competition. Applications of pre-emergence herbicides were applied annually for the first 2–5 years after planting (most sites received treatments for 4 years) to control forbs, grasses and woody vines. During the growing season, shielded, directed sprays of glyphosate were applied to herbaceous plants during the first 3–5 years after planting.

P: planted pine. A combination of the treatments described above was used to control both woody and herbaceous competition during the first 3–5 years after planting. Details of herbicide rates and concentrations are provided elsewhere (Miller *et al.*, 2003a).

Pines were measured for total height in years 1–11, 15 and 20. Diameters at breast height were measured on all pines and hardwoods within measurement plots commencing in year 8. Merchantable pine tree volume outside bark (to a 10-cm top) was calculated according to equations by Tasissa *et al.* (1997). Tree volumes were expanded to an area basis by multiplying the appropriate expansion factor for the measurement plot. Periodic annual increments were calculated on an annual basis for years 8–11 and on a 4- or 5-year basis for years 11–20.

Analyses

Percentage gains due to suppression of herbaceous plants were determined for years 8 and 20 by dividing the stand volume for treatment P

Figure 1. Theoretical examples of stand volumes of *Acer pseudoplatanus* resulting from various stand establishment treatments (top figure). The Type 1 response represents a treatment that produced a 2-year gain in stand development (when compared with the base-line stand represented by the dotted line). The Type 2 response represents a treatment that produced a 3-m increase in site index (base age 50 years). After age 30 years, the Type 3 treatment results in a loss of stand volume. The Type C response represents a treatment that produces a temporary gain in stand volume but after age 25 years the stand volume is equal to the base-level stand. Regardless of response type, the percentage gains in stand volume decline as the stands increase in volume (bottom left figure). When age-shift values are determined for each establishment treatment (bottom right figure), the Type 1 response produces a flat line while the Type 2 figure produces a line that increases over time. Likewise, the Type 3 response eventually results in a negative age shift while the Type C response falls to a zero age-shift at age 25 years.

by stand volume for treatment H, multiplying by 100 and then subtracting 100. Similar calculations using treatments W and W+H gave percentage gains from herbaceous plant suppression in the presence of woody competition.

The age-shift due to controlling herbaceous plants in the absence of woody competition was determined by comparing mean volume production from pine only plots (P) with volume production from H plots where woody plants were controlled. Likewise, the age-shift due to controlling herbaceous plants in the presence of woody competition was determined by comparing means from W+H treatment means with W treatment means. The age-shift for year 8 was determined by comparing the x-coordinate for the P treatment at age 8 years with the H treatment at the same y-coordinate. For example, assume the coordinates were (x = 8 years; y = 39 m^3 ha^{-1}) for the P treatment and (x = 10.47 years; y = 39 m^3 ha^{-1}) for the H treatment. The age-shift in this example will be 2.5 years since all age-shift values were rounded to the nearest 0.1 years. For each site, age-shifts were calculated for years 8–15 and, when appropriate, for ages greater than 15 years.

Another method of computing the age-shift involved comparing height–age curves. For example, the age-shift due to controlling herbaceous plants in the absence of woody competition was obtained by fitting the height–age curve from Burkhart *et al.* (1987) through the nine year heights of the tallest 741 trees ha^{-1} for the H treatment, substituting the age-9-years height from the P treatment into this equation, solving for age, and subtracting 9 years. This method assumes the shape of the height–age curve does not change with vegetation control treatments, but rather the curve is simply shifted along the x-axis.

t-Tests were used to determine whether average age-shift across all sites at a given age was significantly different from zero (α = 0.05). To test the hypothesis that the age-shift value does not decline from ages 8 years to 15+ years, regressions of age-shift versus age were performed for each site. A t-test was then used to determine whether the average slope of these regressions was significantly different from zero. A paired t-test was employed to test the hypothesis that hardwoods affect the age-shift gain. The annual age-shift gain (from year 8 to the final measurement) was determined for plots without woody competition. This value was paired with the annual age-shift gain for woody competition plots at the same site. The null hypothesis was rejected if the t-value was statistically significant.

To aid in interpretation, treatment means were grouped into four competition categories according to hardwood basal area (BA) and shrub competition at age 15 years. The categories were: high hardwood (hardwood BA 4–10 m^2 ha^{-1}), low hardwood (hardwood BA 1–3 m^2 ha^{-1}), no hardwood (hardwood BA < 0.75 m^2 ha^{-1}) and high shrub sites (Miller *et al.*, 2003a). Groupings were developed using SAS Cluster Analysis based on year-15 hardwood BA per hectare and shrub sum of heights per hectare. The high and low hardwood categories were based on H and W+H plots while the no hardwood category was based on P and H plots. Two sites contained >30 000 m ha^{-1} of shrub rootstock and were classified as ‘high shrub’ sites. Since there were only two sites in this category (i.e. all other sites contained <12 000 m of shrub rootstock), data from these sites were not used in this analysis.

After 20 years of data were collected, the herbaceous vegetation treatments at each location were classified into one of four response types (Figure 1). At each site, the slope of the regression equation (age-shift due to herbaceous control = intercept + b (stand age)) was determined. When the age-shift estimate was positive and the slope was <0.18, the treatment was classified as a Type 1 response. Treatments that produce a Type 1 response reduce the age at which a stand reaches maximum annual volume increment but do not increase the carrying capacity of the site (Snowdon and Waring, 1984; Mason, 1992). When age-shift estimate increased over time and the slope of the equation was >0.17, the treatment was classified as a Type 2 response. A Type 2 response occurs when the maximum carrying capacity of the site is increased. When the age-shift declined over time and became negative, the response was classified as Type 3. Treatments that produce a Type 3 response eventually reduce volume production when compared with untreated stands (Richardson, 1993). When the age-shift estimate declined over time and became zero, the treatment was classified as a Type C response. This response occurs when an initial gain in stand volume does not persist and the treated stand ends up with essentially the same stand volume as the untreated stand (Nilsson and Allen, 2003; VanderSchaaf and South, 2004).

Results

Percentage gains

On all 11 sites, percentage gains declined from age 8 to 20 years. Therefore, the hypothesis that percentage gains do not decline as the stand ages was rejected. For plots with no woody competition, the percentage gain averaged 258 per cent at age 8 years but declined to 18 per cent at age 20 years (Table 1).

Plots with no hardwoods

In plots with no hardwoods, controlling herbaceous plants (P treatment) increased volume on all 11 sites when compared with plots with only herbaceous plants (H treatment). The volume increase at age 20 years ranged from 32.4 $m^3 ha^{-1}$ at the Warren site to 77.7 $m^3 ha^{-1}$ for the Tallassee site (Figure 2). The age-shift response at age

Table 1: Age-shift (AS) and percentage gain (PG) values resulting from controlling herbaceous plants in *Pinus taeda* plantations

Site	EAS ht age 9 (years)	AS age 8 (years)	AS age 15 (years)	AS final (years)	Response type	PG age 8 years (%)	PG age 20 years (%)
No hardwoods							
Jena	2.1	2.9	3.9	3.8 (17)	1	298	27
Counce	1.4	1.4	2.1	2.1 (18)	1	303	14
Warren	1.9	1.8	2.0	1.8 (17)	1	150	10
Monticello	0.5	0.9	1.5	1.5 (19)	1	57	12
Liverpool	2.8	2.8	3.6	3.2 (17)	1	360	21
Arcadia	3.4	2.3	2.5	2.4 (18)	1	239	18
Liberty	2.4	2.7	5.5	5.5 (15)	2	128	18
Bainbridge	1.8	2.1	3.4	3.0 (17)	1	150	15
Camp Hill	2.9	3.2	3.3	3.1 (17)	1	285	22
Tallassee	3.3	3.2	3.7	3.6 (17)	1	541	29
Appomattox	1.5	1.3	2.3	2.1 (18)	1	158	17
Average	2.2	2.2	3.1	2.9		243	18
Low hardwoods							
Jena	1.9	1.9	1.2	0.0 (20)	C	164	0
Counce	1.2	1.1	1.0	0.6 (20)	1	318	4
Warren	2.6	2.4	2.7	2.7 (18)	1	431	18
Monticello	1.1	1.6	2.0	2.3 (18)	1	132	19
Average	1.7	1.7	1.7	1.4		261	10
High hardwoods							
Liverpool	2.4	2.4	2.9	2.6 (18)	1	764	21
Arcadia	2.1	1.2	1.6	2.6 (18)	1	307	63
Liberty	2.5	3.3	5.6	5.6 (15)	2	327	16
Bainbridge	0.6	0.6	0.0	−0.3 (20)	3	58	−2
Camp Hill	0.6	0.3	−1.0	−2.0 (20)	3	46	−18
Tallassee	1.4	1.2	−1.4	−2.0 (20)	3	342	−19
Appomattox	0.5	1.0	−0.6	−0.5 (20)	3	363	−6
Average	1.4	1.4	0.9	0.9		315	8

Estimates of age-shift using height gains at age 9 years (EAS ht) and age-shift using merchantable volume yields at ages 8 years, 15 years and the final age-shift (Final) noted at ages 15–20 years (appropriate years in parentheses). The response type for each site was determined by comparing the age-shift at age 8 years with the final year age-shift.

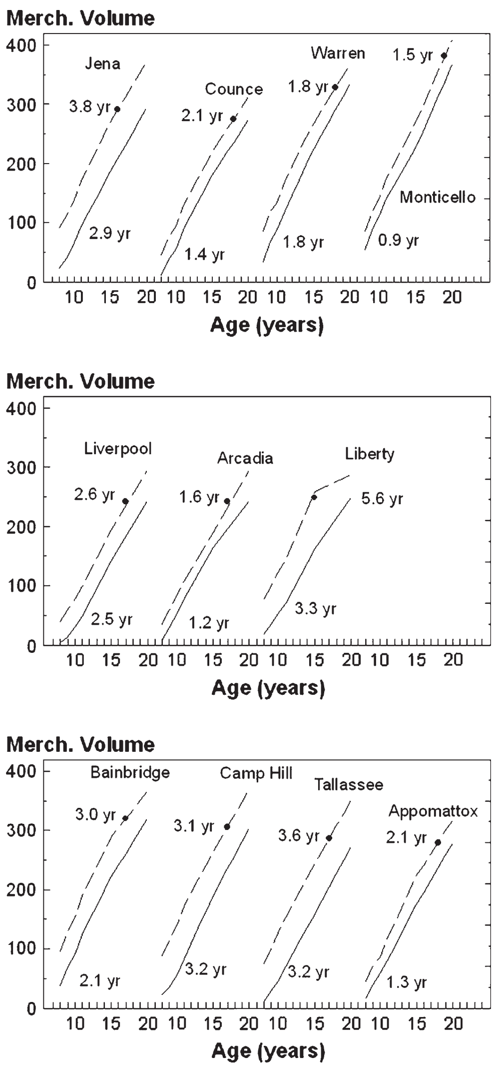


Figure 2. The effect of controlling herbaceous plants on merchantable volume production (m^3 ha^{-1}) of *Pinus taeda* on plots with <0.75 m^2 of woody basal area per hectare at age 15 years. Continuous line = plots with herbaceous plants; dashed line = plots without herbaceous plants. Numbers at the bottom of each graph indicate age-shift determined at age 8 years. Numbers at the top of the graph indicate age-shift determined at the age indicated by the black dot.

8 years was significant (t = 8.84; P < 0.0001) and ranged from 0.9 years to 3.2 years and averaged 2.2 years (Table 1). In the absence of hardwood competition, the age-shift gain resulting from control of herbaceous plants did not decline over time (Figure 3). All but one site had a positive age-shift gain and overall the annual gain (Table 2) was 0.09 years year^{-1} (t = 3.00; P = 0.013). At age 16 years, windthrow damage at the Liberty location resulted in more damage on the P treatment than the H treatment.

Hardwood plots

In the presence of woody competition, controlling herbaceous plants produced an age-shift averaging 1.5 years by age 8 years (t = 5.52; P = 0.003) but this overall average declined to 1.3 years by age 15 years. The hypothesis that the age-shift resulting from suppression of herbaceous competition is not affected by the presence of woody competition was rejected by a paired t-test (t = 2.83; P = 0.018). Therefore, the presence of woody competition reduced the year-gain achieved from suppression of herbaceous plants.

Low hardwood plots

Controlling herbaceous plants (W treatment) increased volume on three out of the four low-hardwood sites when compared with the W+H treatment. By age 20 years, the volume response from controlling herbaceous plants ranged from –0.7 m^3 ha^{-1} at Jena to 64.7 m^3 ha^{-1} for the Monticello site (Figure 4). The age-shift response at age 8 years ranged from 1.1 years to

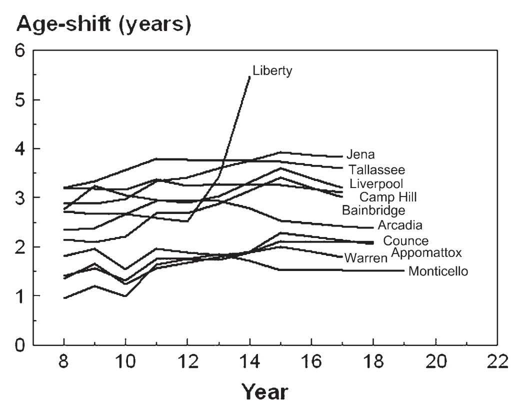


Figure 3. The effect of stand age on the age-shift estimates due to controlling herbaceous plants in 11 *Pinus taeda* plantations on plots with <0.75 m^2 of hardwood basal area per hectare at age 15 years.

Table 2: Slope of the regression equation: age-shift due to herbaceous control = intercept + *b* (stand age)

Site	Hardwood basal area at age 15 years		
	<0.75 m^2 ha^{-1}	1–3 m^2 ha^{-1}	4–10 m^2 ha^{-1}
Jena	0.104	–0.143	–
Counce	0.102	–0.002	–
Warren	0.008	0.029	–
Monticello	0.039	0.070	–
Liverpool	0.015	–	0.109
Arcadia	0.140	–	0.019
Liberty	0.334	–	0.339
Bainbridge	0.140	–	–0.079
Camp Hill	–0.004	–	–0.193
Tallassee	0.039	–	–0.260
Appomattox	0.081	–	–0.209

Slopes reported for sites with no hardwoods at age 15 years (<0.75 m^2 ha^{-1} of hardwood basal area), for sites with low hardwood basal area (1–3 m^2 ha^{-1}) and for sites with high hardwood basal area (4–10 m^2 ha^{-1}).

2.4 years and averaged 1.7 years (Table 1). In the presence of low hardwood competition, the age-shift gain resulting from control of herbaceous plants decreased at two sites and at the remaining two sites there was a slight increase over time (Table 2 and Figure 4).

High hardwood plots

In plots that contained >4 m^2 ha^{-1} of hardwoods at age 15 years, controlling herbaceous plants decreased volume gains on four sites out of seven (Figures 4 and 5). By age 20 years, the volume gain ranged from – 47 m^3 ha^{-1} at Camp Hill to +52.2 m^3 ha^{-1} at Arcadia. The age-shift response at age 8 years ranged from 0.3 years to 3.3 years and averaged 1.4 years. However, this advance in stand development was lost over time as hardwood competition increased. The final age-shift averaged only 0.9 years. In the presence of hardwood competition, the age-shift gain decreased at four out of seven sites (Figure 5).

Interactions

There was a significant treatment interaction between herbaceous and woody control at the Jena site. This is illustrated by slopes with different signs (Table 2). For plots that received woody competition control, the suppression of herbaceous plants resulted in a significant positive slope. As a result, the age-shift increased from 2.1 years (at age 8 years) to 3.8 years (at age 17 years). However, if plots developed a substantial amount of competition mainly from sweetgum (*Liquidambar styraciflua* L.), the early advantage of the pines declined over time and resulted in a Type C response. For each decade that passed, there was about a 1.4 years loss in age-shift and by age 20 years, the pine volume on W+H plots was the same as that for W plots.

The site at Liberty, Mississippi, followed a pattern similar to other sites until age 15 years. However, measurements at age 20 years indicate an increase in the age-shift that is much greater than that observed on the other sites (Figures 3 and 5). This site experienced windthrow and breakage which varied by treatment and also was the only site that shows a trend of slowing periodic annual increment for plots containing herbaceous competition. Stand damage will influence volume gains and subsequent age-shift calculations.

Height as a method of estimating age-shift

On average, estimating age-shift from either age-9-years height or from merchantable volume at age 8 years gave the same result (Table 1). Both methods were correlated with each other (r = 0.87) and provided identical age-shift values in five out of 22 comparisons. In most instances, the difference in estimations was <0.4 years. However, the volume method was slightly better in

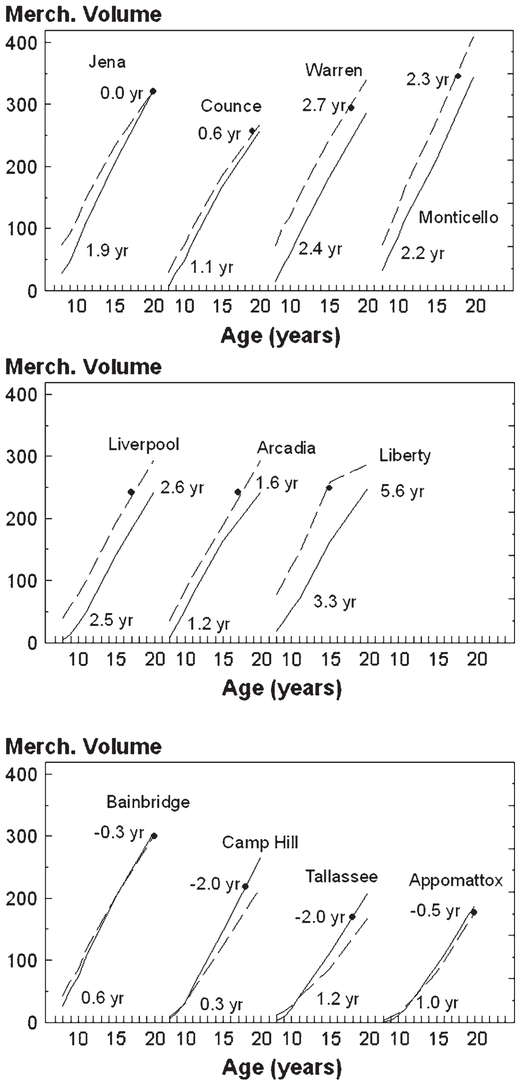


Figure 4. The effect of controlling herbaceous plants on merchantable volume production (m^3 ha^{-1}) of *Pinus taeda* on sites with hardwood competition. Continuous line = plots with herbaceous plants; dashed line = plots without herbaceous plants. Numbers at the bottom of each graph indicate age-shift determined at age 8 years. Numbers at the top of the graph indicate age-shift determined at the age indicated by the black dot.

predicting the final age-shift (at ages 13–20 years). The stand volume method accounted for 68 per cent of the variation in final age-shift ($P > F = 0.0001$) while the height method accounted for 48 per cent of the variation ($P > F = 0.0004$).

Growth response classification

For a majority of sites, reducing herbaceous plants resulted in a Type 1 response but a Type 3 response occurred on four sites with high hardwood competition (Table 1). A Type 2 response occurred at the Liberty site and a Type C response was observed at the Jena site (when a low level of hardwoods was present).

Discussion

The amount of hardwood competition that develops in a stand affects the age-shift response that results from early suppression of herbaceous competition. On sites where the population of woody plant competition is minimal, the complete control of herbaceous plants for 3–5 years can result in a 2–3 years age-shift. However, on sites with a high population of woody plants (i.e. greater than 6 m^2 ha^{-1} at age 15 years), the elimination of herbaceous competition favours the long-term development of hardwoods and this increases their impact on pine growth. This can result in a loss of volume and a negative age-shift (i.e. Type 3 response). This negative response was not detected by age 8 years (Miller *et al*., 1995b)

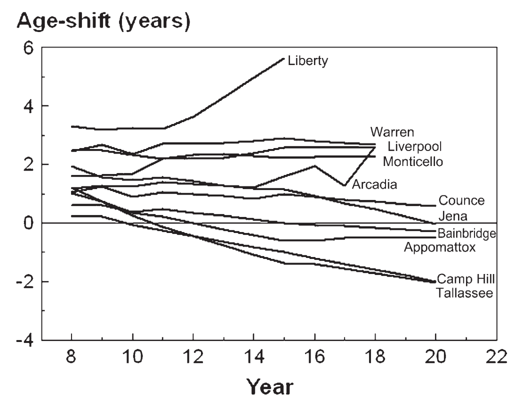


Figure 5. The effect of stand age on the age-shift estimates due to controlling herbaceous plants in 11 *Pinus taeda* plantations on plots with ≥1 m^2 of hardwood competition.

but became evident by 15 years (Miller *et al.*, 2003b). Therefore, a positive increase in height or diameter at breast height at age 4 years does not necessarily mean the treatment qualifies as either a Type 1 or Type 2 response. The response may end up as either a Type 3 or Type C response.

Classifying silvicultural treatments as either Type 1 or Type 2 before the carrying capacity has been reached (i.e. when the current annual increment for volume is zero) carries a degree of risk. For loblolly pine, the current annual increment might not reach zero until after age 50 years (Burkhart *et al.*, 2003). Although we are confident that suppression of herbaceous plants will not increase the carrying capacity of a site, proof will not be available until the COMProject is 50–60 years old. Until that time, we propose that suppression of herbaceous plants will either be a Type 1 response (when hardwood competition is minimal) or a Type 3 response (where hardwood competition is substantially increased by the suppression of herbaceous plants). We believe the Type 2 response noted at the Liberty site can be partly explained by the differential effect of windthrow on treatment plots.

On all sites, percentage gains in merchantable volume declined as the stand aged (Table 1). For plots with no woody competition, controlling herbaceous plants increased volume an average of 258 per cent at age 8 years, 33 per cent at age 15 years and 19 per cent at age 20 years. Therefore, saying that a treatment results in a 15 per cent increase in volume per hectare is meaningless without specifying an age. The assumption that a percentage gain calculated at age 6–8 years will represent an equivalent percentage gain when harvesting at years 20 or years 50 is false. Those who believe percentage gains measured at age 6 years do not decline with stand age will overestimate realized gains if harvest is conducted at year 20 or later (Mead, 2005).

Calculation of age-shift

There are various ways to calculate an age-shift for a silvicultural treatment. If the stand is young and has not produced merchantable trees, then height differences at a given age can be converted to age-shift estimates. This method requires a height–age curve that is appropriate for the site and genotype. Miller *et al.* (1995a) used this method to predict the age-shift for plant control treatments for the COMProject. A second method can be used when the stand is old enough to estimate merchantable stand volume. This method uses an appropriate volume–age curve instead of a height–age curve. Both of these methods can be used when data from only one age is available.

A third method utilizes multiple-year measurements. This method uses the data to develop either a height–age model or volume–age model for each treatment. Once the models have been developed, then the equations are solved to determine the age-shift. This method was used by Kimberly *et al.* (2004) for treatments in New Zealand. The fourth method also uses multiple-year measurements but the data are plotted instead of modelled. The age-shift is determined by examining the difference in x-coordinates when base-level treatment reaches a given y-coordinate.

A fifth method has been suggested due to its simplicity but it is not recommended if the age-shift is much greater than 1 year. This method involves dividing the absolute difference between treatments (either height or stand volume) by the current annual increment. For situations where the calculated age-shift is 2 year or greater (especially for young stands), this method could result in an overestimation of the age-shift.

Modelling suppression of herbaceous weeds

Many growth and yield programs do not account for the control of herbaceous plants. However, these programs can be used when the total suppression of herbaceous weeds results in a Type 1 response. For sites with no hardwood competition, the user could assume a 2- or 3-year age-shift (up to age 23 years or so) for treatments that provided total control of herbaceous plants (for a period of 3–5 years after planting). For sites with hardwood competition, the user might assume a 1.7 years age-shift if the hardwoods did not represent >3 m^2 ha^{-1}. However, for sites with high hardwood competition, the user might assume a negative age-shift of −1 or −2 years (Table 1). This approach was used by Miller *et al.* (1995a) to evaluate the economics of applying herbicides to control herbaceous plants.

There are a few growth and yield programs that allow the user to model herbaceous weed control treatments. For example, two programs in New Zealand (the 'Vegetation Manager' and the 'Central North Island initial growth model'; www.fore.canterbury.ac.nz/igmv2.exe) allow the user to model gains from herbaceous control treatments. In Canada, 'Plant-PC' (www.sfws.auburn.edu/sfnmc/class/plantpc.htm) is a growth model that allows the user to control weeds at planting (Payandeh *et al.*, 1992). In the southern United States, 'Ptaeda2V' (www.vardaman.com/download/ptaedav-demo.exe), 'Ptaeda3' (www.cnr.vt.edu/g&y_coop/demos/ptaeda3_demo_install-3.80.exe), Acorm and the 'Simulator For Managed Stands' (www.fwforestry.com/sims_2003.html) allow the user to model the response of pine to herbaceous treatments. These models use different approaches to modelling gains from suppression of herbaceous plants. Only the Vegetation Manager program in New Zealand provides plots to illustrate the age-shift trends over time.

Some growth and yield models that project volume gains from herbaceous treatments to age 20+ years do not provide a reliable estimate. In some cases, the predicted gains could either be negative or may underestimate realized gains (South, 1999; Westfall, 2001). For example, by age 12–15 years, the Ptaeda3 model forces the height of the herbaceous control treatment to be about the same as that of the control plots (Westfall, 2001). This intentional feature of the program ensures that dominant heights at age 25 years are not greater than the base site index value selected by the user. As a result, the predicted heights of trees provided with herbaceous weed control tend to be similar at age 20 years, regardless of site preparation method or level of competition (Table 3). This causes volume yields to be underestimated for herbaceous control. In some cases, the predicted yield at age 8 years can be as much as 43 m^3 ha^{-1} lower than the observed yield (Westfall, 2001). In other words, for controlling herbaceous plants, Ptaeda3 employs a Type C height response for all sites (i.e. an initial increase in height occurs but this gain is lost by age 25 years and there is no long-term increase in height).

The 'Simulator For Managed Stands' takes a different approach. This model allows herbicide treatments to increase the heights of dominants and co-dominant trees. As a result, predicted results fit more closely to the results observed in the COMProject.

Controlling both woody and herbaceous plants

Overall, suppression of both woody and herbaceous plants for the first 3–5 years after planting increases volume production at age 15 years more than that achieved by suppression of herbaceous plants alone (Miller *et al.*, 2003b). On average, the age-shift due to controlling both plant groups was 3.0 years on low hardwood sites (data not shown) compared with an average of 1.4 years for herbaceous plants only (Table 1). In comparison, the age-shift on high hardwood sites was 6.1 years (when controlling both woody and herbaceous plants) versus 0.9 years when controlling only herbaceous plants. Since the age-shift associated with controlling both woody and herbaceous plants increased over time (4.1–6.1 years), some classify this treatment as a Type 2 response. However, this treatment simply changes the species composition, and is likely to have minimal or no effect on the total carrying capacity (both pine and hardwood biomass). Therefore, this treatment can tentatively be classified as a 'perceived Type 2 response' since it is not a 'true' Type 2 response that increases the total carrying capacity of the site.

Several inconsistencies have emerged when it comes to describing response types. Some say a Type 3 response will eventually result in treated stands falling behind untreated stands (Richardson, 1993) but Mead (2005) only states that the initial growth response is lost. Recently, a few authors added more confusion by ignoring the numbering system used in earlier papers. They define a Type 3 response as one that increases the carrying capacity of the site (Harrison *et al.*, 2002; Prescott and Blevins, 2005)! In some papers, the 'age-shift response' is not mentioned. For example, Morris and Lowery (1988) illustrated three response types: (A) site improved, (B) early height increase maintained, and (C) a transient increase where the height of the untreated stand eventually exceeds that of the treated stand. Both 'A' and 'B' increased the maximum carrying capacity (as indicated by an increase in site index) and therefore both would be classified as a 'Type 2' response. However, since we are not aware of any silvicultural treatment that will result in an early growth difference of 1 m which is 'maintained' throughout the rotation,

Table 3: Predicted response (age 20 years) of planting 1497 *Pinus taeda* seedlings per hectare with four site preparation methods, two levels of hardwood competition (percentage of total basal area in hardwoods at crown closure) and three levels of duration of herbaceous plant suppression using the Ptaeda3 growth and yield model

		Duration of herbaceous control		
Site preparation	Basal area in hardwoods (%)	None	1 year	2 years
			Dominant height (m)	
Chop + burn	0	18.1	18.2	18.2
Discing	0	18.3	18.3	18.3
Bedding	0	18.3	18.3	18.3
Shear + pile	0	18.1	18.2	18.2
			Green tonne per hectare	
Chop + burn	0	245.9	249.5	260.7
Discing	0	244.8	241.9	246.1
Bedding	0	254.0	243.0	248.8
Shear + pile	0	255.5	254.4	264.1
			Age-shift (years)	
Chop + burn	0	0	0.2	1.0
Discing	0	0	–0.2	0.1
Bedding	0	0	–0.9	–0.4
Shear + pile	0	0	–0.1	0.6
			Dominant height (m)	
Chop + burn	40	18.1	18.2	18.2
Discing	40	18.3	18.3	18.3
Bedding	40	18.3	18.3	18.3
Shear + pile	40	18.1	18.2	18.2
			Green tonne per hectare	
Chop + burn	40	162.7	161.6	170.8
Discing	40	165.4	155.6	165.0
Bedding	40	165.7	163.9	168.3
Shear + pile	40	167.9	171.9	181.6
			Age-shift (years)	
Chop + burn	40	0	–0.5	2.0
Discing	40	0	–1.7	–0.1
Bedding	40	0	–0.3	0.4
Shear + pile	40	0	0.9	3.3

This example is for a Coastal Plain site with a base site index (base age 25 years) of 21 m. Years gains calculated using yield over age curves for the respective site preparation treatment with no herbaceous control.

we believe the 'early height increase maintained' or response is only hypothetical. In contrast, the 'age-shift' response does exist and does not result in a height gain that remains constant over time. Figure 1 is provided to assist in clarification of response types and their designation.

Economic calculations

When economists project early gains from herbaceous treatments, they either use projections from a growth and yield model, or they assume an age-shift (Huang and Teeter, 1990; Miller *et al.*, 1995a). Typically, economists do not extrapolate percentage gains observed at age 10 years to predict harvest volumes. This is because percentage gains in volume decline as the stand ages (Figure 1 and Table 1). Knowing the percentage gain in either height or volume at age 9 years does not improve ones ability to predict volume gains at age 20–30 years.

On the other hand, calculating an age-shift at age 9 years can be a useful tool for a forest economist. For example, if a 2- or 3-year age-shift can be achieved by spending \$67 ha^{-1} in herbicide treatments, then suppression of herbaceous plants will be economical (Huang and Teeter, 1990). However, if it requires an input of \$445 ha^{-1} to achieve a 1.6-year age-shift, then the effort is not likely to be beneficial (Miller *et al.*, 1995a). Our data suggest that, in addition to the cost of herbaceous weed control, economists should account for the risks associated with hardwood competition before concluding that the treatment will be economical.

The Ptaeda3 model produces yield outputs from various silvicultural treatments (Burkhart *et al.*, 2003). Economic outputs from this model suggest that for a 20-year rotation, it can be profitable to suppress herbaceous plants for 1 or 2 years if the site has no hardwoods and has been prepared with chopping and burning. However, for the same site, it would not be economical to suppress herbaceous weeds if the site has been bedded (Table 3). Since Ptaeda3 predicts many Type C and Type 3 responses when no hardwoods are present, we question the validity of this interaction.

This program also suggests that the marginal economic gain associated with 2 years of herbaceous weed control is greater than that expected from 1 year of control (Table 3). For example, on hardwood-free sites that have been prepared by chopping and burning, the model predicts that 1 year of herbaceous control increases volume production by 3.6 green tonnes ha^{-1} (Table 3). Providing an additional year of control results in an additional 11.2 green tonnes ha^{-1}. These results run contrary to previous studies with *Pinus taeda* that show that the marginal gains (i.e. volume gain per herbicide application) are greater for 1 year of weed control than for 2 years of control (Lauer *et al.*, 1993).

Projections from Ptaeda3 also suggest that with a high level of hardwood competition, the suppression of herbaceous plants for 2 years can result in an increase in volume production and will potentially be economical on 'sheared and piled' sites. Since data from the COMProject show volume losses for sites that have 40 per cent of the basal area in hardwoods, we question the validity of the response predicted by Ptaeda3.

Conclusion

The age-shift method of evaluating the response of herbaceous vegetation management is superior to the percentage gain method. On sites with little or no hardwood competition, predictions of 'age-shift' based on stand volume of loblolly pine remain relatively stable from ages 8 to 18 years. In contrast, percentage gains are a function of stand size and therefore the percentages decline as the stand ages. Overestimations of realized gains can occur when percentage gains measured at young stand ages are applied to predicted gains at harvest (e.g. age 20+ years).

The realized age-shift response from herbaceous control is a function of the amount of hardwoods that develop within a stand. In stands where the amount of hardwood competition is high, age-shift estimates will decline as the stand develops. For these sites, age-shift estimates made at young stand ages will overestimate the realized gains at harvest (e.g. age 20 years).

Estimates of age-shift can differ depending upon the method of calculation. For a given site, the age-shift predictions based on height measurements may differ from those based on stand volume measurements. However, on average, both methods are likely to give similar results.

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